WIMP Dark Matter: Complementarity of LHC, ILC and Direct Searches
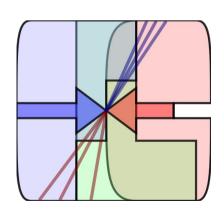
Snowmass Energy Frontier
Workshop, BNL
April 3, 2013
J.List (DESY)

Today's Menue

- Introduction

- Exclusion / discovery reach

    - LHC & Direct Detection

    - ILC

- After discovery: WIMP property determination and model-discrimination

    - LHC

    - ILC

- Conclusions

Introduction

Perfect introduction for this talk from Chip Brock this morning:

Excerpts: Questions from the Cosmic Conveners:*

> The message from the LHC seems to be that with data in hand, we consistently outperform expectations for extraction of Higgs properties. **How much is there really for an ILC to contribute?** What key assumptions are we making now that we could relax with ILC inputs?

Let's try to answer this one as far as WIMP dark matter is concerned!

Effective Operator Approach

- Assume *fermion* / vector / scalar WIMP

- Plus heavy mediator particle:

  - Scalar / vector / axial-vector / ...

  - s-channel / t-channel / loop!

- Integrate mediator out
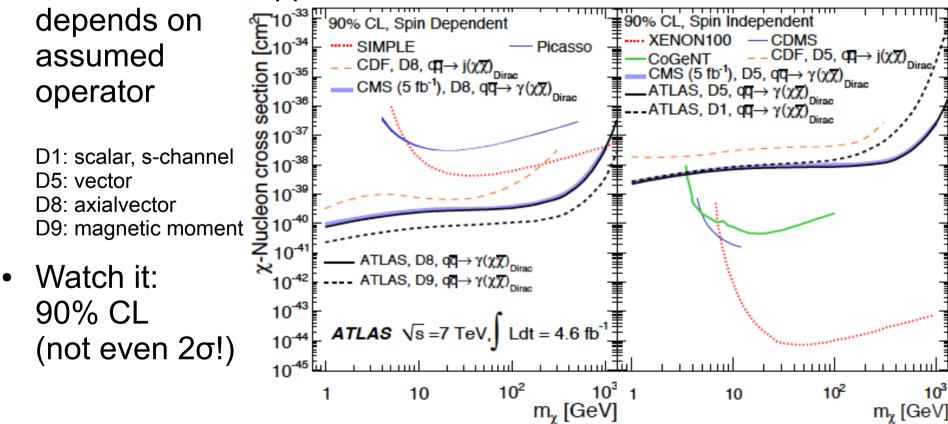 → "contact interation"
      scale Λ (or M_*)

$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell), \quad \text{(vector)}$$
$$\mathcal{O}_S = (\bar{\chi}\chi)(\bar{\ell}\ell), \quad \text{(scalar, } s-\text{channel)}$$
$$\mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell), \quad \text{(axial} - \text{vector)}$$
$$\mathcal{O}_t = (\bar{\chi}\ell)(\bar{\ell}\chi), \quad \text{(scalar, } t-\text{channel).}$$

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Discovery / Exclusion Reach

LHC and direct searches

- Direct crossing relation: Both probe WIMP-nucleon interaction

- Unique relation LHC (ex: ATLAS monophoton search) ↔ direct searches

- Translation from pp → XX to WIMP-nucleon cross-section
  depends on assumed operator

  D1: scalar, s-channel
  D5: vector
  D8: axialvector
  D9: magnetic moment

- Watch it:
  90% CL
  (not even 2σ!)
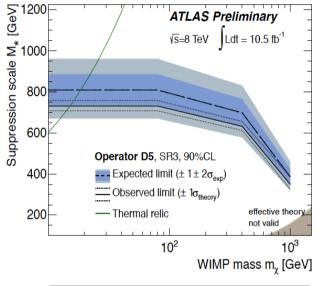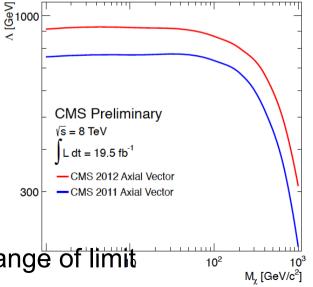
LHC: Limits on Λ
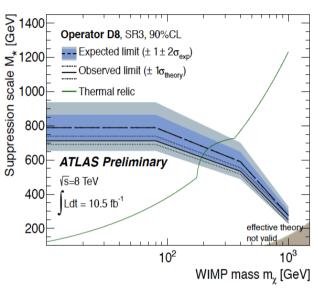
Eg monojet search:
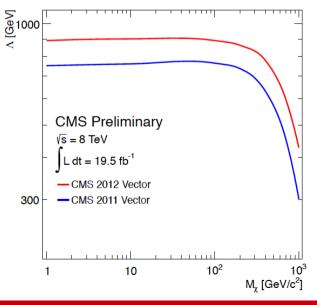
- Vector / Axialvector limits ~900 GeV for light WIMPs

- Note:

  - at 90% CL

  - Scalar limits ~3x weaker

  - "Thermal relic" line assumes 100% annihilation to qq via this operator

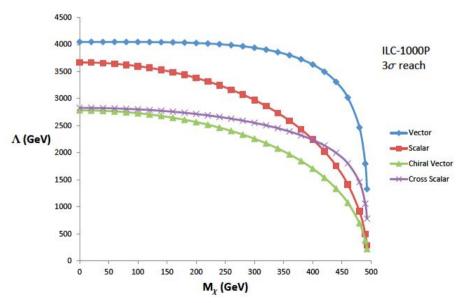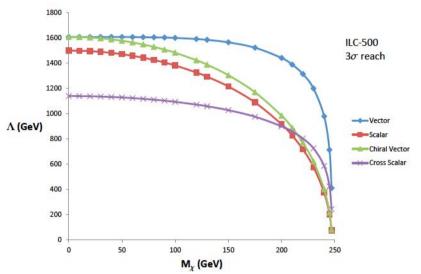 - 7 → 8 TeV & 5 → 20 fb⁻¹ => ~150 GeV change of limit
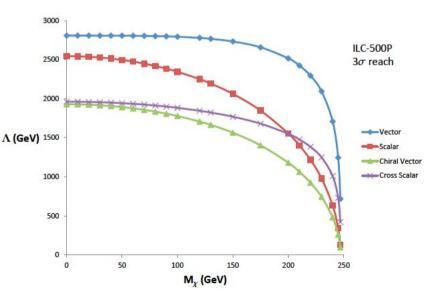
ILC: Projected sensitivity on Λ

Monophoton search:

- 3σ observation reach (99.x% CL)

- Polarised case $P(e^-, e^+) = (+80\%, -50\%)$: improves by ~factor 2

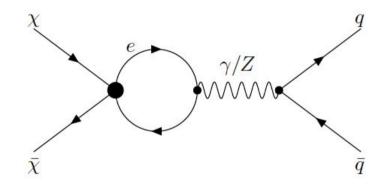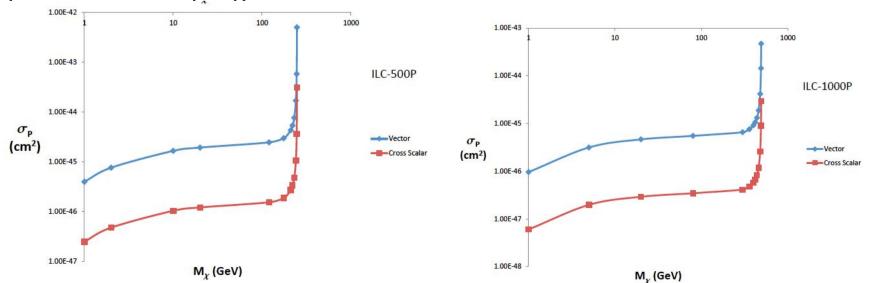- Reach up to 3-4 TeV, far beyond E_{CM}

e⁺e⁻ and pp / XN

- LC probes WIMP – *lepton* interaction

- Relation to WIMP – nucleon interaction highly model-dependent

- Is suppression scale the same for quarks and leptons?

    - A priori not!

    - Ex: t-channel exchange of "squark / slepton"

    - Direct couplings vs loop couplings

=> *LC provides orthogonal and independent information,*

regardless whether LHC discovers or just excludes

How to relate e⁺e⁻ to Direct Searches?

- Will be model-dependent!

- Most conservative, ie minimal "unavoidable" X-Nucleon cross-section:

    - Assume no tree-level coupling to quarks

    - Leaves us with loop contributions

- Direct searches need sensitivity of
  ~ $10^{-46..47}$ cm² to rule out model-indenpently lepton-WIMP couplings observable at ILC
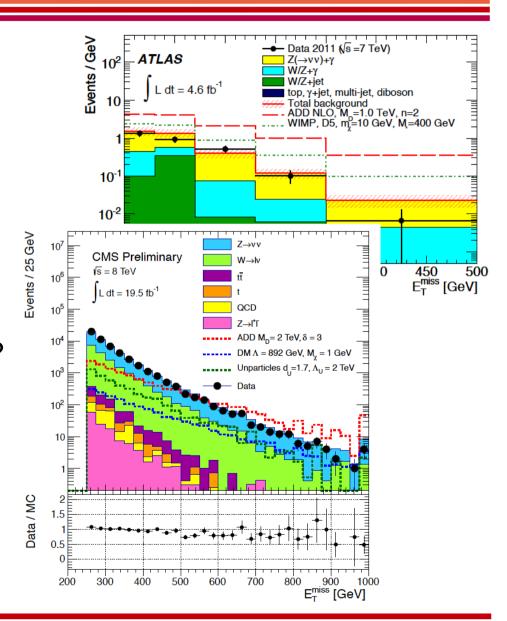
After a discovery:
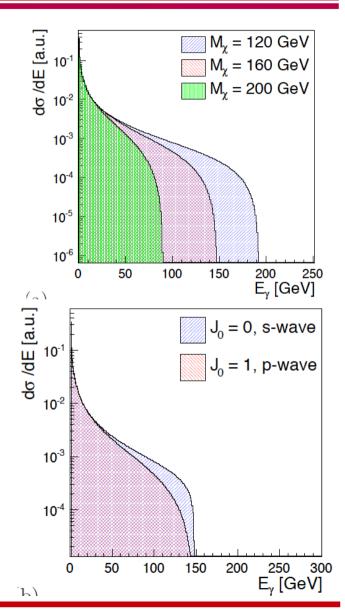# WIMP property determination
and model-discrimination

LHC observables

- **Eg Etmiss in**
  - Mono-photon
  - Or mono-jet channel

- **Signals from various new physics models look rather similar...**

- **How well could we discriminate eg a WIMP from an ADD signal?**

- **Is this being studied?**

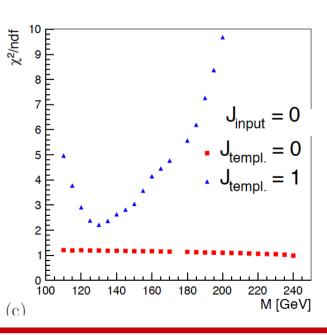- **Is this an interesting study for the Snowmass process?**

ILC observables

- Mono-photon: E_γ spectrum offers

  – Clean endpoint due to kinematic limit
  $\to$ mass

  – Shape -> dominant partial wave
  (s-channel: Spin of mediator)

  – Can eg distingish SUSY-WIMP vs UED
  [cf 0902.2000 [hep-ph] Konar et al]

- What about

  – Detector resolution?

  – Beam energy spectrum?

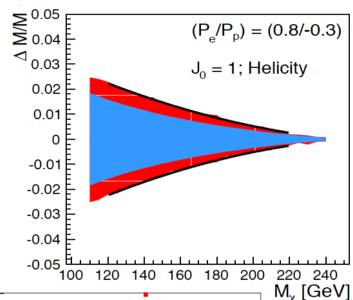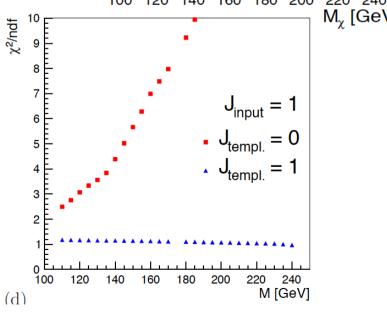 – Backgrounds? (physics & instrumental)

  => full detector simulation study

WIMP characterisation

- Mass resolution
eg ILC @ 500 GeV, 500fb^{-1},
$P(e^+,e^-) = (-30\%,80\%)$

  - 1-2% level

    - Dominated by conservative assumption on knowledge of beam energy spectrum

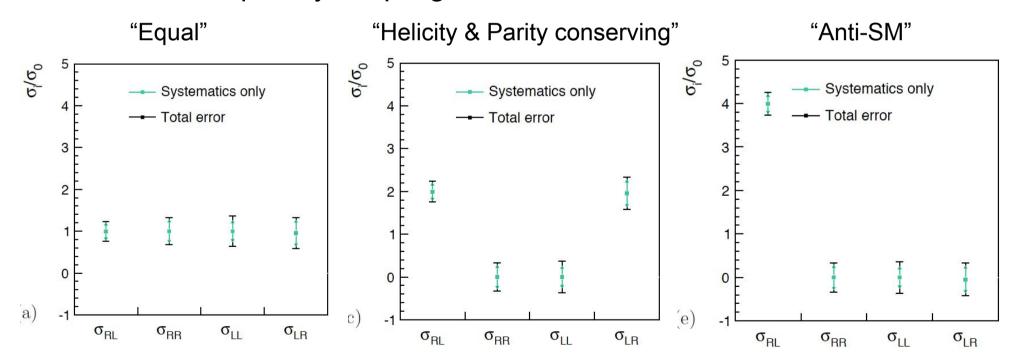- Dominant partial wave determination: correct hypothesis clearly favoured

Helicity Structure of WIMP-Fermion Interaction

- Measure cross-section with different beam helicities! Eg |P| = 80% / 30%, all four sign combinations (lumi split 200fb^{-1} +-/-+, 50fb^{-1} ++/--) NB: the more positron polarisation, the better!

- Three examplatory coupling scenarios:

"Equal"   "Helicity & Parity conserving"   "Anti-SM"
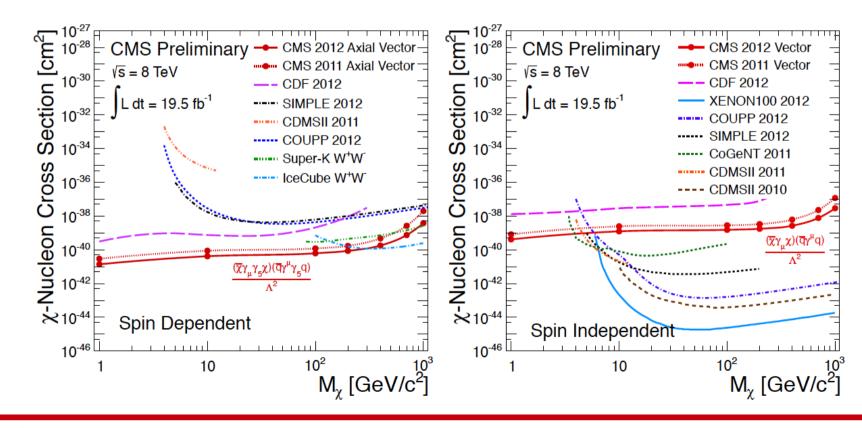
Clear distinction possible!

Conclusions

- ILC provides

    – orthogonal information to LHC and direct searches by probing WIMP-lepton interaction bottom-up, testing contact interaction scales ip to 3-4 TeV

    – great opportunities for WIMP property determination (mass: 1-2%, helicity structure, spin of mediator) $\rightarrow$ model discrimination

- Snowmass opportunities:

    – LHC (maybe already worked on?):
      - Reach for HL-LHC? (2,3,5 sigma)
      - Property determination at HL-LHC?
    – ILC:
      - Effective opperator approach in full detector simulation
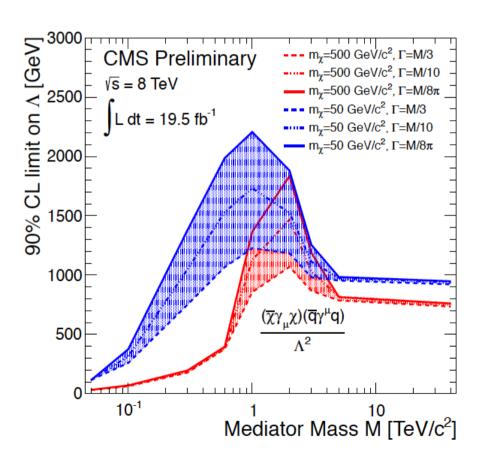   - Update to TDR beam parameters and detectors

LHC and direct searches: mono-jets
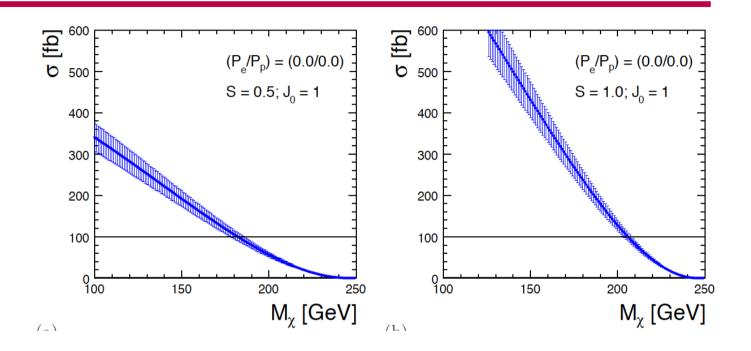
- Roughly similar sensitivity

LHC and direct searches: mono-jets

- Mediator kinematically accessible

Thermal WIMP cross-section prediction for ILC

Introduction

- Cosmology → 25% of universe = Dark Matter

- One possibility: WIMPs

- Bottom-up approach:

  - assume only WIMP, don't rely on other new particles

  - Only know <sigma v> for XX → ffbar
    (Caveat: resonant or coannihilation!)

  - Or: effective operator approach

- Direct searches for primordial WIMPs in WIMP-nucleon scattering

- Searches for direct WIMP production at collider:

  - pp → XX gluon / gamma

  - ee → XX gamma